New physics upper bound on the branching ratio of $B_s \to l^+l^-$

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We consider the most general new physics effective Lagrangian for $b \to sl^+l^-$. We derive the upper limit on the branching ratio for the processes $B_s \to l^+l^-$ where $l = e, \mu$, subject to the current experimental bounds on related processes, $B \to Kl^+l^-$ and $B \to K^*l^+l^-$. If the new physics interactions are of vector/axial-vector form, the present measured rates for $B \to (K, K^*)l^+l^-$ constrain $B(B_s \to l^+l^-)$ to be of the same order of magnitude as their respective Standard Model predictions. On the other hand, if the new physics interactions are of scalar/pseudo-scalar form, $B \to (K, K^*)l^+l^-$ rates do not impose any constraint on $B_s \to l^+l^-$ and the branching ratios of these decays can be as large as present experimental upper bounds. If future experiments measure $B(B_s \to l^+l^-)$ to be $\geq 10^{-8}$ then the new physics giving rise to these decays has to be of the scalar/pseudo-scalar form.

The rare decays of B mesons involving flavour changing neutral interaction (FCNI) $b \to s$ has been a topic of great interest for long. Not only will it subject the standard model (SM) to accurate tests but will also put strong constraints on several models beyond the SM. In the SM, FCNI occur only via one or more loops. Thus the rare decays of B mesons will provide useful information about the higher-order effects of the SM. Recently, the very high statistics experiments at B-factories have measured non-zero values for the branching ratios for the FCNI processes $B \to (K, K^*)l^+l^-$ [1, 2],

$$
\begin{aligned}
Br(B \to Kl^+l^-) &= (4.8^{+1.0}_{-0.9} \pm 0.3 \pm 0.1) \times 10^{-7}, \\
Br(B \to K^*l^+l^-) &= (11.5^{+2.6}_{-2.4} \pm 0.8 \pm 0.2) \times 10^{-7}.
\end{aligned}
\tag{1}
$$

These branching ratios are close to the values predicted by the SM [3]. However, the SM predictions for them contain about $\sim 15\%$ uncertainty coming from the hadronic form factors. Still, it is worth considering what constraints these measurements impose on other related processes.

The effective Lagrangian for the four fermion process $b \rightarrow sl^+l^-$ gives rise to the exclusive semi-leptonic decays such as $B \rightarrow Kl^+l^-$ and $B \rightarrow K^*l^+l^-$ and also to purely leptonic decays $B_s \rightarrow l^+l^-$, where $l = e, \mu$. (From here onwards, the symbol l represents either e or μ.) Relation between semi-leptonic and purely leptonic B-decays, arising from FCNI generated by heavy Z' boson exchange, was briefly considered in [4, 5]. The SM predictions for the branching ratios for the decays $B_s \rightarrow e^+e^-$ and $B_s \rightarrow \mu^+\mu^-$ are $(7.58 \pm 3.5) \times 10^{-14}$ and $(3.2 \pm 1.5) \times 10^{-9}$ respectively [6]. The large uncertainy in the SM prediction for these branching ratios arises due to the 12% uncertainty in the B_s decay constant and 10% uncertainty in the measurement of V_{ts}. These branching ratios have been calculated in various new physics models. In models with Z'-mediated FCNI, one has $B(B_s \rightarrow \mu^+\mu^-) < 5.8 \times 10^{-8}$ [7] which is about 20 times larger than the SM prediction. Due to the increased precision in the measurement of $B(B \rightarrow (K, K^*)l^+l^-)$, this bound can be improved and the present calculation attempts to do so. $B(B_s \rightarrow l^+l^-)$ are also calculated in multi Higgs doublet models. These models are classified into two types. In the first type, there is natural flavour conservation (NFC) and there are no FCNI at tree level. In such models, there is an additional loop contribution to FCNI, where a charged Higgs boson exchange replaces the SM W-exchange. In a two Higgs doublet model with NFC, branching ratio for $B_s \rightarrow \mu^+\mu^- \geq 10^{-8}$ is possible [8]. In the second type, flavour changing processes do occur at tree level, mediated by flavour changing neutral scalars (FCNS's). In such models also a branching ratio of about 10^{-8} for $B_s \rightarrow \mu^+\mu^-$ can be achieved [7]. From the experimental side, at present, there exist only upper bounds $B(B_s \rightarrow e^+e^-) < 5.4 \times 10^{-5}$ [9] and $B(B_s \rightarrow \mu^+\mu^-) < 5.0 \times 10^{-7}$ [10].

In this paper, we consider the most general four fermion effective Lagrangian for $b \rightarrow sl^+l^-$ transition due to new physics. We derive upper bounds on the branching ratios for $B_s \rightarrow e^+e^-$ and $B_s \rightarrow \mu^+\mu^-$ by demanding that the predictions of this new physics Lagrangian for $B \rightarrow K^*l^+l^-$ and $B \rightarrow Kl^+l^-$ should be consistent with the current experimental values.

The most general effective Lagrangian for $b \rightarrow sl^+l^-$ transitions due to new physics can be written as,

$$L_{eff}\left(b \rightarrow sl^+l^-\right) = L_{VA} + L_{SP} + L_T \tag{2}$$

where, L_{VA} contains vector and axial-vector couplings, L_{SP} contains scalar and psuedo-scalar couplings and L_T contains tensor couplings. L_T does not contribute to $B_s \rightarrow l^+l^-$ because $\langle 0|\bar{s}\sigma^{\mu\nu}b|B_s(p_B)\rangle = 0$. Hence we will drop it from further consideration.

First we will assume that the new physics Lagrangian contains only vector and axial-vector couplings. We parametrize it as

$$L_{VA}\left(b \to s l^+ l^-\right) = \frac{G_F}{\sqrt{2}} \left(\frac{\alpha}{4\pi s_W^2}\right) \bar{s}(g_V + g_A\gamma_5)\gamma_\mu \bar{l}(g_V' + g_A'\gamma_5)\gamma^\mu l. \tag{3}$$

Here the constants g and g' are the effective couplings which charecterise the new physics. From the above equation, we get $B_s \to l^+ l^-$ matrix element to be

$$M\left(B_s \to l^+ l^-\right) = (g_A g_A')\frac{G_F}{\sqrt{2}} \left(\frac{\alpha}{4\pi s_W^2}\right) \langle 0 \left|\bar{s}\gamma_5\gamma_\mu b\right| B_s\rangle\langle l^+ l^- \left|\bar{l}\gamma_5\gamma^\mu l\right| 0\rangle. \tag{4}$$

Only the axial vector parts contribute for both the hadronic and leptonic parts of the matrix element. Substituting $\langle 0 \left|\bar{s}\gamma_5\gamma_\mu b\right| B_s\rangle = -if_{B_s}p_{B\mu}$, in Eq. (4) we get

$$M\left(B_s \to l^+ l^-\right) = -i2m_l f_{B_s}(g_A g_A')\frac{G_F}{\sqrt{2}} \left(\frac{\alpha}{4\pi s_W^2}\right) \bar{u}(p_l)\gamma_5 v(p_{\bar{l}}). \tag{5}$$

As we are considering only vector and axial vector currents, helicity suppression is still operative for the $B_s \to l^+ l^-$ decay amplitude. The calculation of the decay rate gives

$$\Gamma_{NP}(B_s \to l^+ l^-) = \frac{G_F^2 f_{B_s}^2}{8\pi} \left(\frac{\alpha}{4\pi s_W^2}\right)^2 (g_A g_A')^2 m_{B_s} m_l^2. \tag{6}$$

Thus the decay rate depends upon the value of $(g_A g_A')^2$. To estimate the value of $(g_A g_A')^2$, we consider the related decays $B \to K^* l^+ l^-$ and $B \to K l^+ l^-$, which also receive contributions from the effective Lagrangian in Eq. (3). In deriving Eq. (6), we dropped terms proportional to m_l^2/m_B^2, as their contribution is negligible. We will make the same approximation in calculating the decay width of semi-leptonic modes also.

We first consider the process $B \to K^* l^+ l^-$. Here we will have to calculate the following hadronic matrix elements [3]:

$$\begin{aligned}
\langle K^*(p_{K^*}) \left|\bar{s}\gamma_\mu b\right| B(p_B)\rangle &= i\epsilon_{\mu\vartheta\lambda\sigma}\epsilon^\nu(p_{K^*})(p_B + p_{K^*})^\lambda(p_B - p_{K^*})^\sigma V(q^2) \\
\langle K^*(p_{K^*}) \left|\bar{s}\gamma_5\gamma_\mu b\right| B(p_B)\rangle &= \epsilon_\mu(p_{K^*})(m_B^2 - m_{K^*}^2)A_1(q^2) - (\epsilon.q)(p_B + p_{K^*})_\mu A_2(q^2)
\end{aligned} \tag{7}$$

where $q = p_{l^+} + p_{l^-}$. In the above equation, a term proportional to q_μ is dropped because its contribution to the decay rate is proportional to m_l^2/m_B^2. It is assumed that the q^2 dependence of these form factors is well described by a pole fit:

$$\begin{aligned}
V(q^2) &= \frac{V}{(m_B + m_{K^*})(1 - q^2/m_B^2)} \\
A_i(q^2) &= \frac{A_i}{(m_B + m_{K^*})(1 - q^2/m_B^2)}.
\end{aligned}$$

The decay rate is

$$\Gamma_{NP}(B \to K^* l^+ l^-) = \frac{1}{2} \left(\frac{G_F^2 m_B^5}{192\pi^3} \right) \left(\frac{\alpha}{4\pi s_W^2} \right)^2 (g_V'^2 + g_A'^2) I_{VA}, \tag{8}$$

where I_{VA} is the integral over the dilepton invariant mass $(z = q^2/m_B^2)$. Under the assumption that $A_1 \approx A_2$, I_{VA} is given by

$$I_{VA} = g_V^2 V^2 \int_{z_{min}}^{z_{max}} dz \frac{z}{1-z} C_1(z) + g_A^2 A_1^2 \int_{z_{min}}^{z_{max}} dz \frac{z}{1-z} C_2(z), \tag{9}$$

where,

$$C_1(z) = 2 \left(1 + \frac{m_{K^*}}{m_B} \right)^{-2} \Phi(z)$$

$$C_2(z) = \left[3 \left(1 - \frac{m_{K^*}}{m_B} \right)^2 + \left(\frac{m_B}{2m_{K^*}} \right)^2 \left(1 + \frac{m_{K^*}}{m_B} \right)^{-2} \left(z - \frac{5m_{K^*}^2}{m_B^2} \right) \Phi(z) \right].$$

with $\Phi(z) = (1-z)^2 + 4z \left(m_{K^*}/m_B \right)^2$. The limits of integration for z are given by $z_{min} = (2m_l/m_B)^2$ and $z_{max} = (1 - m_{K^*}/m_B)^2$. From equation (8) we see that, the value of $(g_A g_A')^2$ can be determined from the measured rate of $\Gamma(B \to K^* l^+ l^-)$, provided the value of $g_V^2 (g_V'^2 + g_A'^2)$ is known. For this we consider the decay of $B \to K l^+ l^-$.

The matrix element neccessary in this case is [3]

$$\langle K(p_K) | \overline{s} \gamma_\mu b | B(p_B) \rangle = (p_B + p_K)_\mu f_{KB}^+(q^2), \tag{10}$$

where again a term proportional to q_μ is dropped. The q^2 dependence of the formfactor, again, is approximated by a single pole with mass $\approx m_B$,

$$f^+(q^2) = \frac{f^+(0)}{1 - q^2/m_B^2}. \tag{11}$$

The decay rate is given by

$$\Gamma_{NP}(B \to K l^+ l^-) = g_V^2 (g_V'^2 + g_A'^2) \left(\frac{G_F^2 m_B^5}{192\pi^3} \right) \left(\frac{\alpha}{4\pi s_W^2} \right)^2 \left(\frac{f^+(0)}{2} \right)^2. \tag{12}$$

We demand that the maximum value of this decay rate is the measured experimental value, (i.e.)

$$\Gamma_{exp} = \Gamma_{NP}. \tag{13}$$

With this assumption we calculate the upper bound on the decay rate of $B_s \to l^+ l^-$, arising due to L_{VA}, given in Eq. (3). Using Eqs. (8), (12) and (13), we get

$$g_V^2 (g_V'^2 + g_A'^2) = \frac{B_{Exp}(B \to K l^+ l^-)}{3.45 [f^+(0)]^2} \times 10^4 \tag{14}$$

and

$$g_A^2(g_V'^2 + g_A'^2) = \frac{B_{Exp}(B \to K^* l^+ l^-) \times 10^4 - 1.58 V^2 g_V^2 (g_V'^2 + g_A'^2)}{8.94 A_1^2}. \tag{15}$$

In our calculation, we take the formfactors to be [11]

$$f^+(0) = 0.319^{+0.052}_{-0.041}$$

$$V = 0.457^{+0.091}_{-0.058}$$

$$A_1 = 0.337^{+0.048}_{-0.043}, \tag{16}$$

and use experimental values of $B \to (K, K^*)l^+ l^-$ given in [2]. Adding all errors in quadrature, we get

$$g_V^2(g_V'^2 + g_A'^2) = (1.36^{+0.53}_{-0.44}) \times 10^{-2}$$

$$g_A^2(g_V'^2 + g_A'^2) = (6.76^{+4.04}_{-3.48}) \times 10^{-3}. \tag{17}$$

Thus the maximum value $(g_A g_A')^2$ can have, is

$$(g_A g_A')^2 = (6.76^{+4.04}_{-3.48}) \times 10^{-3} \tag{18}$$

The branching ratio for $B_s \to l^+ l^-$, due to L_{VA}, to be

$$B(B_s \to e^+ e^-) = 1.06 \times 10^{-10} \cdot f_{B_s}^2 (g_A g_A')^2$$

$$B(B_s \to \mu^+ \mu^-) = 4.54 \times 10^{-6} \cdot f_{B_s}^2 (g_A g_A')^2. \tag{19}$$

Substituting $f_{B_s} = 240 \pm 30$ MeV [12] and the maxmimum value for $(g_A g_A')^2$ from Eq. (18), we get

$$B(B_s \to e^+ e^-) = 4.06^{+2.65}_{-2.34} \times 10^{-14}$$

$$B(B_s \to \mu^+ \mu^-) = 1.74^{+1.13}_{-1.00} \times 10^{-9} \tag{20}$$

Therefore the upper bounds on the branching ratios are,

$$B(B_s \to e^+ e^-) < 6.71 \times 10^{-14}$$

$$B(B_s \to \mu^+ \mu^-) < 2.87 \times 10^{-9} \tag{21}$$

at 1σ and

$$B(B_s \to e^+ e^-) < 1.20 \times 10^{-13}$$

$$B(B_s \to \mu^+ \mu^-) < 5.13 \times 10^{-9} \tag{22}$$

at 3σ.

These rates are close to the SM predictions. The reason for this is quite simple. The decay rate for an exclusive semi-leptonic process can be written as

$$\Gamma = (c.c.)^2 (f.f.)^2 \text{phase space},\qquad(23)$$

where $c.c.$ is the coupling constant and $f.f.$ is the form factor. The measured rates for the exlcusive semi-leptonic deays are close to the SM predictions. And we assumed that the new physics predictions for these processes are equal to their corresponding experimental values. Also, the same set of form factors are used in both SM and new physics calculations. Thus the assumption that new physics predictions for semi-leptonic branching ratios are equal to their experimental values (which in turn are equal to their SM predictions) implies that the couplings of new physics are very close to the couplings of the SM. This is why our new physics prediction for the purely leptonic mode is also close to the SM prediction. Therefore, new physics, whose effective Lagrangian for $b \to sl^+l^-$ consists of only vector and axial vector currents, cannot boost up the rate of $B_s \to l^+l^-$ due to the present experimental constraints coming from the decays $B \to Kl^+l^-$ and $B \to K^*l^+l^-$.

For the reasons explained above, using a different set of form factors, as for example those given in [13], will not change the upper bound on $B_s \to l^+l^-$ significantly. In fact, we find that the change is less than 10%.

We can obtain a more stringent upper bound on $(g_A g_A')^2$ by the following procedure. We equate the new physics contribution for $\Gamma(B \to (K, K^*)l^+l^-)$ to the difference between the experimental value and the SM contribution. This, in turn, leads to a much more stringent upper bound on contribution of L_{VA} to $B_s \to l^+l^-$. In fact, at 1σ, this bound is consistent with 0. At 3σ we get

$$
\begin{aligned}
B(B_s \to e^+e^-) &< 7.89 \times 10^{-14} \\
B(B_s \to \mu^+\mu^-) &< 3.37 \times 10^{-9},
\end{aligned}
\qquad(24)
$$

which are again comparable to the SM predictions. Comparing these results with the ones obtained by previous assumption, we see that there is not much difference in the branching ratios. This occurs due to the relatively large errors in both the experimental measurements and SM predictions for $\Gamma(B \to (K, K^*)l^+l^-)$. Thus we conclude that the presently measured values of $B \to (K, K^*)l^+l^-$ do not allow any large boost in the contribution of L_{VA} to $B_s \to l^+l^-$.

We now consider the new physics effective Lagrangian to consist of scalar/pseudoscalar couplings,

$$L_{SP}\left(b \to sl^+l^-\right) = \frac{G_F}{\sqrt{2}} \left(\frac{\alpha}{4\pi s_W^2}\right) \bar{s}(g_S + g_P\gamma_5)b\,\bar{l}(g_S' + g_P'\gamma_5)l. \tag{25}$$

The matrix element for the decay $B_s \to l^+l^-$ is given by,

$$M\left(B_s \to l^+l^-\right) = \frac{G_F}{\sqrt{2}} \left(\frac{\alpha}{4\pi s_W^2}\right) g_P\langle 0\,|\bar{s}\gamma_5 b|\,B_s\rangle \left[g_S'\bar{u}(p_l)v(p_{\bar{l}}) + g_P'\bar{u}(p_l)\gamma_5 v(p_{\bar{l}})\right] \tag{26}$$

On substituting,

$$\langle 0\,|\bar{s}\gamma_5 b|\,B_s\rangle = -i\frac{f_{B_s}m_{B_s}^2}{m_b + m_s}, \tag{27}$$

we get,

$$M\left(B_s \to l^+l^-\right) = -ig_P\frac{G_F}{\sqrt{2}} \left(\frac{\alpha}{4\pi s_W^2}\right) \frac{f_{B_s}m_{B_s}^2}{m_b + m_s} \left[g_S'\bar{u}(p_l)v(p_{\bar{l}}) + g_P'\bar{u}(p_l)\gamma_5 v(p_{\bar{l}})\right], \tag{28}$$

where m_b and m_s are the masses of bottom and strange quark respectively. Here we take the quark masses from Particle Data Group obtained under $\overline{MS}$ scheme [14]. We see that in this case there is no helicity supression *i.e.* the rates for the decays $B_s \to e^+e^-$ and $B_s \to \mu^+\mu^-$ will be the same provided g_P' and g_S' for both electrons and muons are the same. The calculation of the decay rate gives,

$$\Gamma_{NP}(B_s \to l^+l^-) = g_P^2(g_S'^2 + g_P'^2)\frac{G_F^2}{16\pi} \left(\frac{\alpha}{4\pi s_W^2}\right)^2 \frac{f_{B_s}^2 m_{B_s}^5}{(m_b + m_s)^2}. \tag{29}$$

The Branching ratio is given by,

$$B(B_s \to l^+l^-) = 0.17\frac{f_{B_s}^2 g_P^2(g_S'^2 + g_P'^2)}{(m_b + m_s)^2}. \tag{30}$$

To estimate the value of $g_P^2(g_S'^2 + g_P'^2)$, we again consider the related decay $B \to K^*l^+l^-$. Its matrix element, due to L_{SP} is given by,

$$M(B \to K^*l^+l^-) = \frac{G_F}{\sqrt{2}} \left(\frac{\alpha}{4\pi s_W^2}\right) g_P\langle K^*\,|\bar{s}\gamma_5 b|\,B\rangle \left[g_S'\bar{u}(p_l)v(p_{\bar{l}}) + g_P'\bar{u}(p_l)\gamma_5 v(p_{\bar{l}})\right] \tag{31}$$

as $\langle K^*\,|\bar{s}b|\,B\rangle = 0$. The pseudoscalar hadronic matrix element is given by [15],

$$\langle K^*\,|\bar{s}\gamma_5 b|\,B\rangle = -i\left(\frac{2m_{K^*}}{m_b - m_s}\right) A_0(q^2)(q \cdot \epsilon) \tag{32}$$

The q^2 dependence of the formfactor is described by a pole fit,

$$A_0(q^2) = \frac{A_0(0)}{(1 - q^2/m_B^2)}. \tag{33}$$

The full calculation gives,

$$\Gamma_{NP}(B \to K^* l^+ l^-) = \left(\frac{G_F^2 m_B^5}{256\pi^3}\right) \left(\frac{\alpha}{4\pi s_W^2}\right)^2 \left(\frac{2m_{K^*}}{m_b - m_s}\right)^2 [A_0(0)]^2 g_P^2(g_S'^2 + g_P'^2) \left(\frac{m_B}{2m_{K^*}}\right)^2 I_{SP}$$

(34)

where,

$$I_{SP} = \int_{z_{min}}^{z_{max}} dz \left[\frac{z}{(1-z)^2}\right] \left[\left(1 + \frac{m_{K^*}^2}{m_B^2} - z\right)^2 - \frac{4m_{k^*}^2}{m_B^2}\right]^{\frac{3}{2}}.$$

(35)

The limits of integration for the dilepton invariant mass ($z = q^2/m_B^2$) are once again given by $z_{min} = (2m_l/m_B)^2$ and $z_{max} = (1 - m_{K^*}/m_B)^2$. Now we assume that the maximum value of this decay rate is the measured experimental value. Thus from Eq. (34), we get

$$g_P^2(g_S'^2 + g_P'^2) = \frac{(m_b - m_s)^2 B_{Exp}(B \to K^* l^+ l^-)}{2.16 [A_0(0)]^2} \times 10^3.$$

(36)

Taking the value of $A_0(0)$ to be $0.471_{-0.059}^{+0.127}$ [11], we get

$$g_P^2(g_S'^2 + g_P'^2) = 4.02_{-1.41}^{+2.41} \times 10^{-2}$$

(37)

Substituting the value of $g_P^2(g_S'^2 + g_P'^2)$ in Eq. (30) we get,

$$B(B_s \to l^+ l^-) = 2.10_{-0.93}^{+1.38} \times 10^{-5}.$$

(38)

The upper bound on $B(B_s \to \mu^+\mu^-)$ from the above equation is much higher than the present experimental upper bound [10]. Thus we see that the measured values of $B(B \to (K, K^*)l^+l^-)$ do not provide any useful constraint on L_{SP} contribution to $B(B_s \to \mu^+\mu^-)$. The significance of this result is that if a future experiment, such as LHC-b [16] observes $B(B \to \mu^+\mu^-) \geq 10^{-8}$, one can confidently assert that the *new physics giving rise to this large a branching ratio must necessarily be of scalar/psuedoscalar type.* Comparing the expression in Eq. (30) to the experimental upper bound in [10], we obtain the bound

$$g_P^2(g_S'^2 + g_P'^2) \leq 10^{-3}$$

(39)

Conclusions: We considered the most general effective Lagrangian for the flavour changing neutral process $b \to s l^+ l^-$, arising due to new physics. We showed that the present experimental values of $B(B \to (K, K^*)l^+l^-)$ set strong bounds on $B(B_s \to l^+l^-)$ if the effective Lagrangian is product of vectors/axial-vectors. Given that the above semi-leptonic decay rates of B-mesons are comparable to their SM predicted values, we showed that the

rate for purely leptonic decays of B_s can't be much above the their SM predicted values. We have also derived a 3σ upper bound on $B(B_s \to \mu^+\mu^-) < 5 \times 10^{-9}$ arising from Z'-mediated flavour changing neutral currents. If the effective Lagrangian for $b \to sl^+l^-$ is product of scalars/psuedoscalars then present experimental values of $B(B \to (K, K^*)l^+l^-)$ do not lead any useful bound on $B(B_s \to l^+l^-)$. This leads us to the very important conclusion that, if a future experiment observes $B_s \to l^+l^-$ with a branching ratio greater than 10^{-8}, then the new physics responsible for this decay must of be scalar/psuedoscalar type.

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